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Visual search processes of Coast Guard aircrewmen

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VISUAL SEARCH PROCESSES OF COAST GUARD AIRCREWMEN

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

VISUAL SEARCH PROCESSES OF
COAST GUARD AIRCREWMEN

by

David Allen Jones

December 1974

Thesis Advisor: N. R. Forrest

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Block 20 - ABSTRACT (Cont.)

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The probability of seeing section indicates that the probability of detection in the foveal vision area is proportional to the size and contrast of the target. Finally, the inverse cube law of detection is utilized to calculate the probability of detection vs. coverage factor for patterned searches.

Visual Search Processes of

Coast Guard Aircrewmen

by

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requirements for the degree of

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December 1974

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This thesis presents the various components of the visual search process as it applies to Coast Guard lookouts. It begins with a description of the human eye and follows with an introduction to detection lobe theory. Next, the most distinct region of daylight vision, the foveal vision area, is discussed.

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I. INTRODUCTION

This thesis introduces the elements of visual search and builds them into a model which is applicable to a typical Coast Guard airborne search. For this thesis, a typical search is one which looks like this:

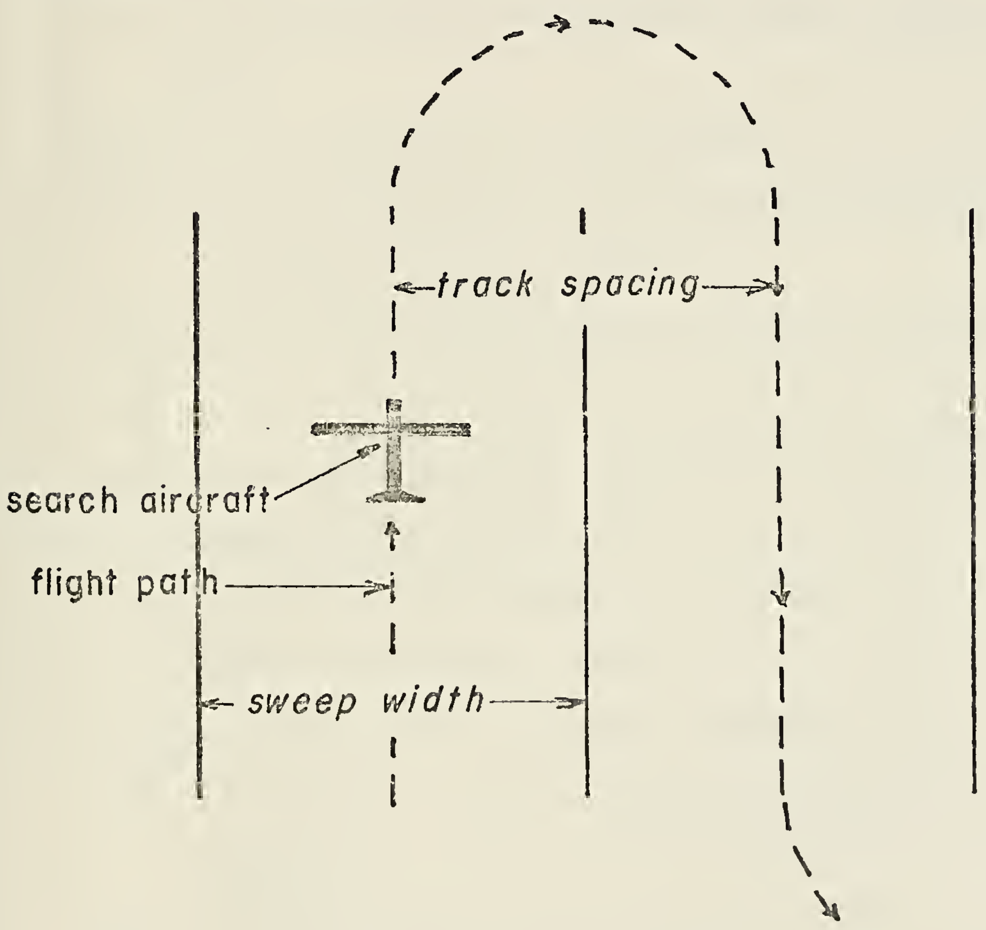

Figure 1. Typical Airborne Search Pattern

The searcher is assumed to be seated in the search aircraft in such a position that he can direct his gaze along a line perpendicular to the flight path out to the limit of the

sweep width. The sweep width is thus defined as the distance which is visually swept out by the lookout(s) in the search aircraft. If the sweep width were two miles, the lookout on each side of the aircraft would look out to a distance of one mile measured perpendicular to the flight path of the search aircraft. Other assumptions about the lookout are:

1) The aircrewman is motivated toward finding the target.
2) He is relaxed and non-fatigued.
3) He has good visual acuity and does not use vision aids such as binoculars.
4) He is familiar with the characteristics of the target.
5) He is able to judge the distance to the edge of the sweep width accurately.
6) His vision is unimpaired by haze, etc., out to the limit of the sweep width.

Assumptions about the search aircraft are:

1) It is at an altitude of at least 500 and less than 2500 feet.
2) It's velocity is less than 250 knots.
3) It follows a perfect flight pattern through the search area, i.e., all tracks are parallel to each other and of the proper length, thus insuring uniform search area coverage.

Assumptions about the target are:

1) It is non-evasive.

2) It is motionless.

Assumptions about the search environment are:

1) The search takes place during daylight.

2) The search takes place over the ocean.

The first section of the thesis describes the eye of the searcher. As he is carried along by the search aircraft, the lookout moves his eye in and out along a line perpendicular to the line of flight. This results in a zig-zag eye pattern across the sweep width illustrated in Figure 2.

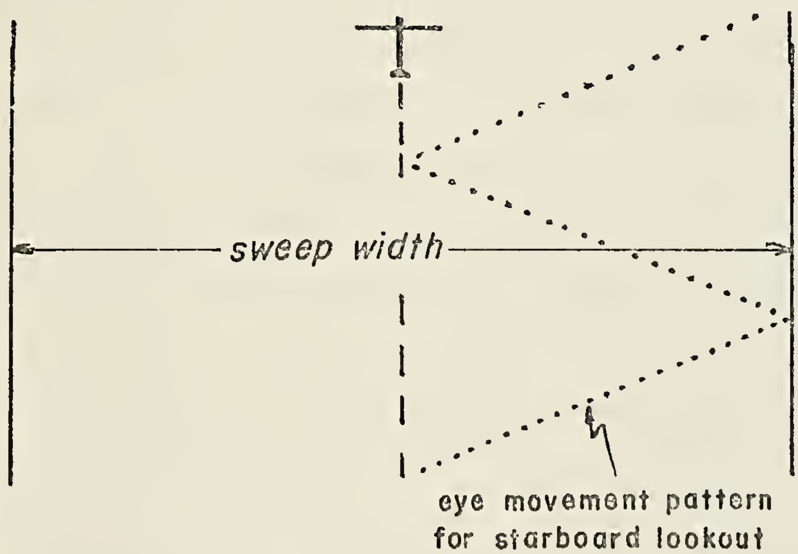

Figure 2. Lookout Eye Movement Pattern

In this thesis, the eye is considered to be capable of recognizing the target only during periods of no motion. These periods of no movement are called <u>fixations</u>. The eye movement pattern now becomes a series of separate fixation areas as shown in Figure 3.

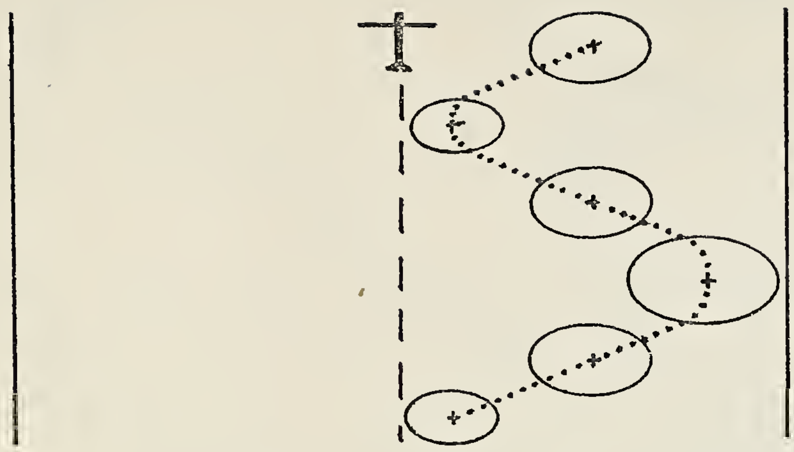

Figure 3. Pattern of Lookout's Fixation Area Pattern

The fixation area of the eye is actually a slice of the detection lobe of the eye. The detection lobe is described in the next section of the thesis as a theoretical volume of vision which can be thought of as being attached to the front of the eye and moving with it. (See Figure 4.) For example, for the target ranges assumed in this thesis, the detection lobe fixation areas are those associated with the narrow part of the detection lobe. This portion of the lobe is called the foveal vision area since visual discrimination at long distances can only occur if the object being looked at is imaged upon the fovea of the eye. These foveal vision areas are discussed in the next section and can be computed for various target ranges.

The natural fixation rate in free search is three fixations per second and each fixation lasts about a quarter of a second. In one second, therefore, the foveal fixation areas in the sweep width might look like those shown in Figure 5.

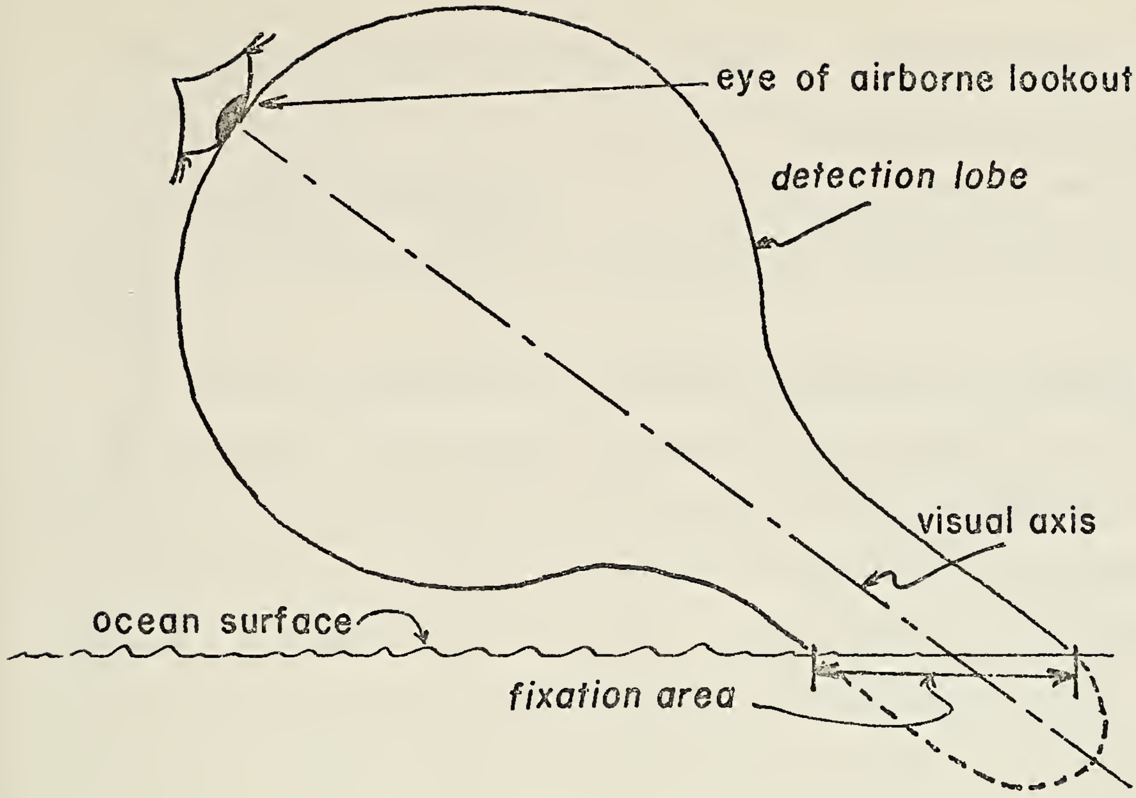

Figure 4. Side View of Detection Lobe

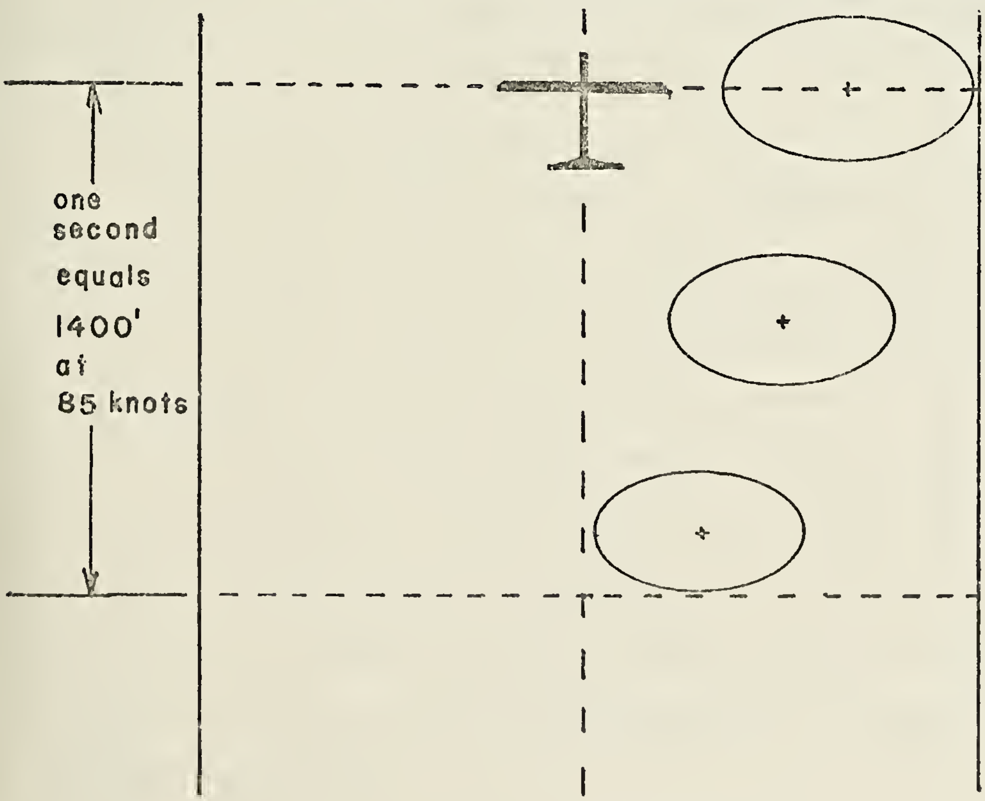

Figure 5.
Relationship of Fixation Areas in One Second of Search

Within this area of foveal fixation, the probability of detection is shown to be a function of <u>the size of the target</u> and <u>the target's contrast</u>, i.e., the difference between the luminance (brightness) of the target and the background (ocean).

In the next section, the <u>Inverse Cube Law of Detection</u> is presented. It is used to compute the probability of detection as a function of the coverage factor, W/S, where W is the sweep width and S is the track spacing, or distance between adjacent search aircraft flight paths. A coverage factor of one (1.0) means that W = S or that the entire search area comes within the searcher's vision. Similarly, a coverage factor of one-half (0.5) would mean that W was half the value of S and only one-half of the search area comes within the searcher's vision. This relationship is illustrated by Figure 6.

The relationship between coverage factor and probability of detection is significant because it allows the searcher the ability to modify his coverage factor dependent upon the particular characteristics of the search. For example, the National Search and Rescue Manual, CG 308, has a table of sweep widths for visual search which shows the searcher what value of sweep width he should use in any given search situation. In essence, this is where the real world enters the model. The different variables used to enter the sweep width table are:

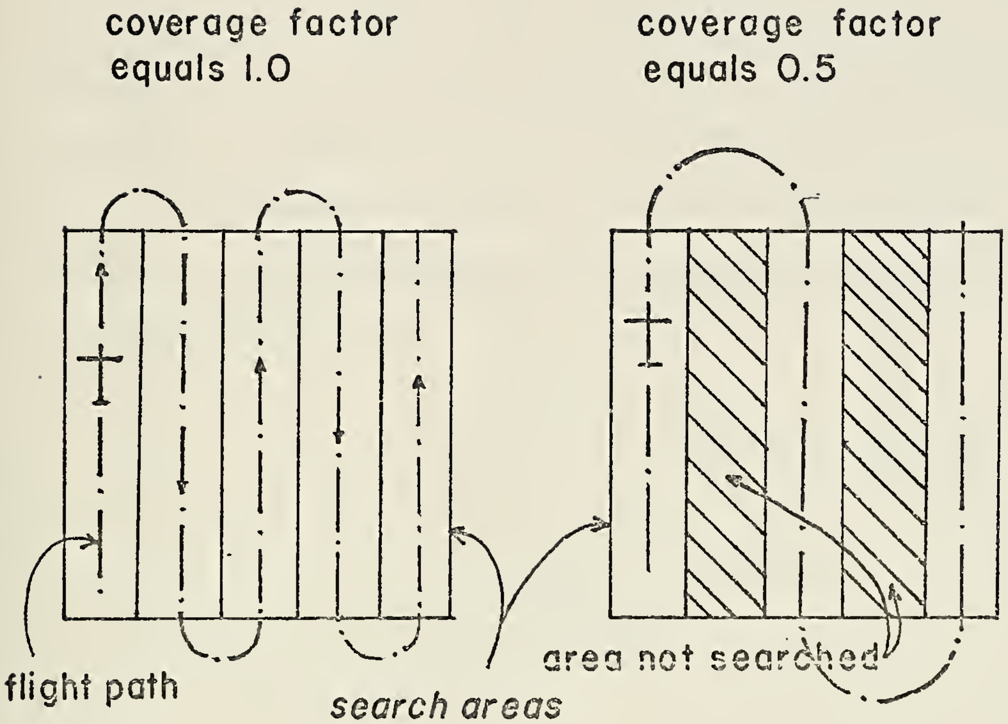

Figure 6. Coverage Factors for Parallel Track Searches

1) Target type and size.

2) Search altitude.

3) Meteorological visibility.

4) Wind, as it affects the number of whitecaps on the ocean.

5) Percentage of cloud cover.

For example, if the search object is a boat less than 30 feet long, the search altitude is 500 feet, the visibility is five miles, the wind is 10 knots and the cloud coverage is 90%, then the value of sweep width, W, from the table is 2.16

nautical miles. For a boat between 60 and 90 feet long, a search altitude of 1000 feet, a visibility of 15 miles, a wind of 5 knots and a 30% cloud cover, the value of W is 9.12 nautical miles. The searcher can then set his track spacing, S, to the value which will yield the desired probability of detection. For a coverage factor of one (1.0), i.e., the sweep width equal to the track spacing, the inverse cube law indicates the probability of detection is approximately 78%.

II. THE EYE

In visual search, the primary detector of targets is the human eye which consists essentially of a spherical sac with opaque walls and a transparent front, called the cornea.

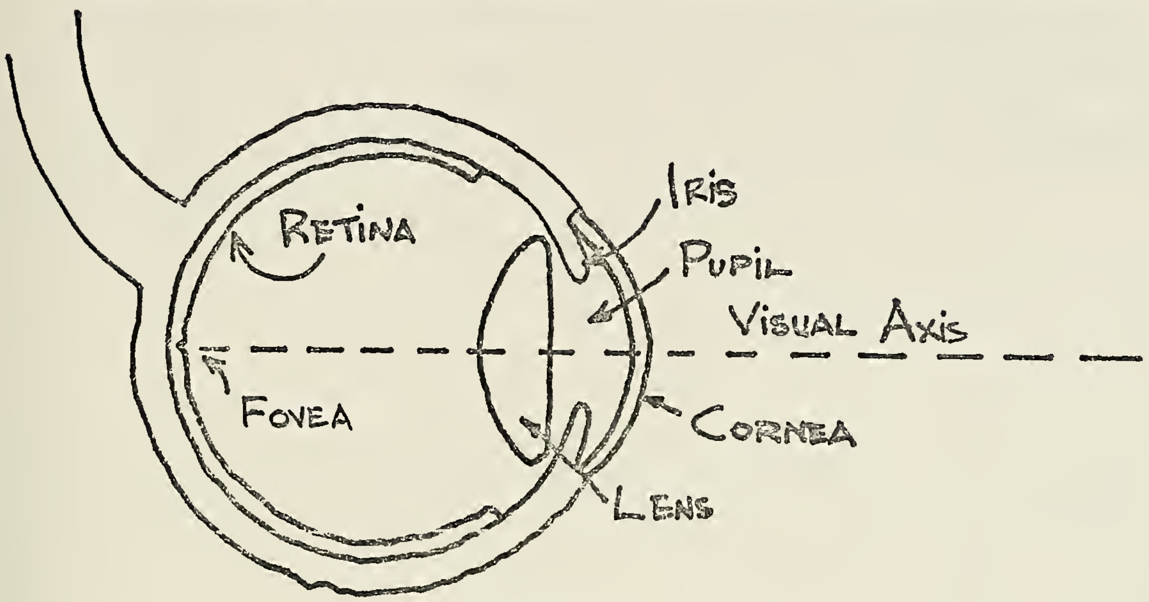

Figure 7. The Eye

The cornea and the crystalline lens together constitute a compound lens which forms an image on the retine. The pupil varies in size and limits the amount of light entering the eye. The retina is similar to the film in a camera and consists of two types of receptors known as rods and cones. The rods serve for night vision and are incapable of distinguishing color. The cones are used for daylight and color vision. The central part of the retina is known as the fovea and is one end of the visual axis. The fovea is the region of the most distinct daylight vision because it contains only cones. As the distance from the fovea across the

retina increases, the density of cones decreases while the density of rods increases and then decreases. This means that in daylight a target can be seen most clearly by looking straight at it, while at night the best view is obtained by looking about six degrees to one side. Unlike radar, which scans continuously, the eye moves in jumps while searching, and is capable of vision only during periods of little or no motion. These periods are called fixations and last for about 0.25 seconds [Ref. 1].

III. DETECTION LOBES

Reference 2 states that there is a volume of detectability associated with each fixation; this volume is called a detection lobe or eye lobe diagram. This lobe is well adapted to the function it has performed for thousands of years - human survival. Distant objects which do not pose immediate threat can be seen only if imaged on the narrow field of the fovea (the central area of the retina which contains only cones). The closer the target, and therefore the more immediate the threat, the larger the image on the fovea and retina. A typical detection lobe for a small target is shown in Figure 8. Theta, θ, is the angle about the visual axis

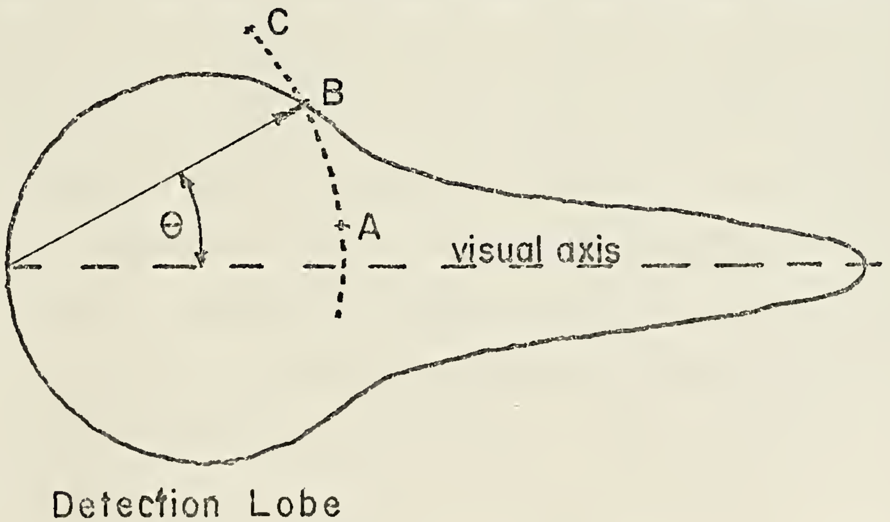

Figure 8. Typical Detection Lobe Diagram

within which the target can be seen. Theta is large for near targets and decreases as target range decreases. Since the closest a target would come in airborne search is about

500 feet, this thesis is concerned with the narrow or foveal vision area of the detection lobe. R is the target range within which the target can be seen (if the target angle is less than or equal to θ). In other words, a target at point A or B can be seen, but a target at point C cannot be seen (even though it is at a range equal to that of points A and B) because it is at an angle to the visual axis which is greater than θ.

The detection lobe can be thought of as being attached to the eye and moving with it. Any target which comes within the lobe will be seen, and any target which falls outside it will be missed. This is analogous to using a searchlight whose beam has a cross section similar to the detection lobe cross section in the preceding figure. Actually, the boundary of the detection lobe is not as sharp as the one shown. Some targets just inside the lobe will be missed (due to target characteristics such as contrast, size, relative motion, etc.) and some targets just outside the lobe will be seen. However, since the boundary can be defined so these two effects compensate for each other, a sharp boundary can be assumed with little or no loss in applicability to actual search situations.

Equations from which detection lobes may be computed are:

$$C = 1.75\ \theta^{\frac{1}{2}} + 45.6\ \theta R^2/A \quad (0.8<\theta<90) \qquad (1)$$

$$C = 1.57 + 36.5\ R^2/A \quad (\theta<0.8) \qquad (2)$$

In these equations, C is the target contrast or the absolute value of the difference in brightness between the target and the background, divided by background brightness (in percent).

Brightness in this context means <u>luminance</u>. The difference between brightness and luminance is: luminance refers to the physical quantity of light intensity per unit area, while brightness refers to the sensation which results from a certain amount of luminance. In other words, an ordinary light bulb viewed in full daylight would not appear very bright, but the same light viewed by a dark-adapted eye at night would appear extremely bright. The sensation, brightness has changed, but the physical properties of the light source, the lamp, have remained the same. The normal units of measurement of luminance are: candela/measure of area. For example, candela/ square feet where candela = 0.98 international candles [Ref. 3].

According to Ref. 4, detection lobes can also be constructed so they contain an area of finite probability of detection. An example of the lobe equation for an area with a 57 percent probability of detection per glimpse for a circular target is:

$$C_t = 1.75\ \theta^{\frac{1}{2}} + \frac{19\theta}{X^2} \qquad (0.8°<\theta<90°) \qquad (3)$$

In this form, the equation specifies the threshold apparent contrast of the target (C_t)[1], relative to its background, for a circular target located θ degrees off the visual axis and at a range such that its diameter subtends an angle of X minutes at the eye of the observer.

---

[1] Threshold apparent contrast is defined as the average of the contrast (difference between target luminance and background luminance) above which the target could always be seen and the contrast below which it could never be seen.

IV. FOVEAL VISION AREAS

In Ref. 5, the area covered during a single fixation is treated in a somewhat different manner. The area contained within an image focused only upon the fovea (area of most distinct daylight vision) is calculated. Since the fovea covers a circular area about one and one-half millimeters in diameter, it is a simple matter to compute the size of an area of foveal vision at varying distances from the eye. For example, a penny held eight and one-half inches from the eye covers the foveal area. For an airborne observer at an altitude of 200 feet, the foveal vision areas are as shown in Figure 9.

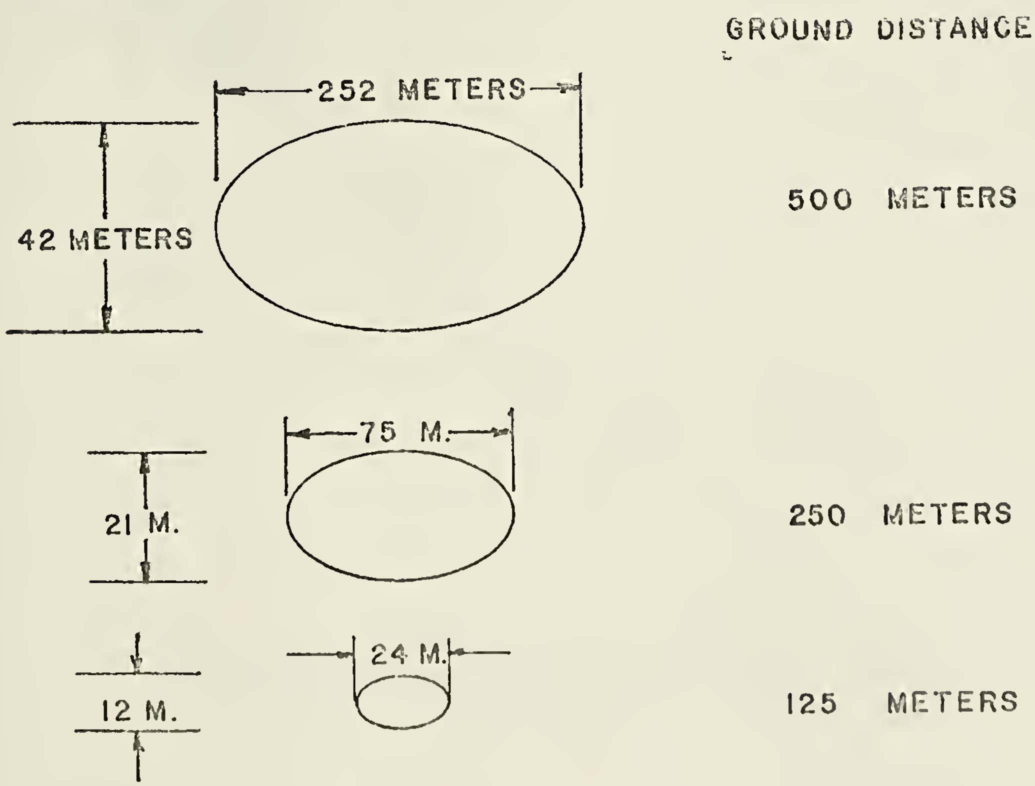

Figure 9. Foveal Vision Areas for Different Ranges

These ellipses were generated using the following formula in Ref. 5:

$$Y = S'S\text{sine } \beta/h \qquad (4)$$

Where Y is the length of the foveal area (appx 1.5 mm), h is the observer's altitude, S is the slant range to the most distant portion of the foveal area, S' is the slant range to the closest portion of the foveal area, and β is the angle of foveal vision.

Reference 6 states that a visual angle of one degree produces an image of 0.29 mm on the fovea. A foveal diameter of 1.5 mm would then correspond to a β of approximately five degrees.

These relationships are illustrated by Figure 10.

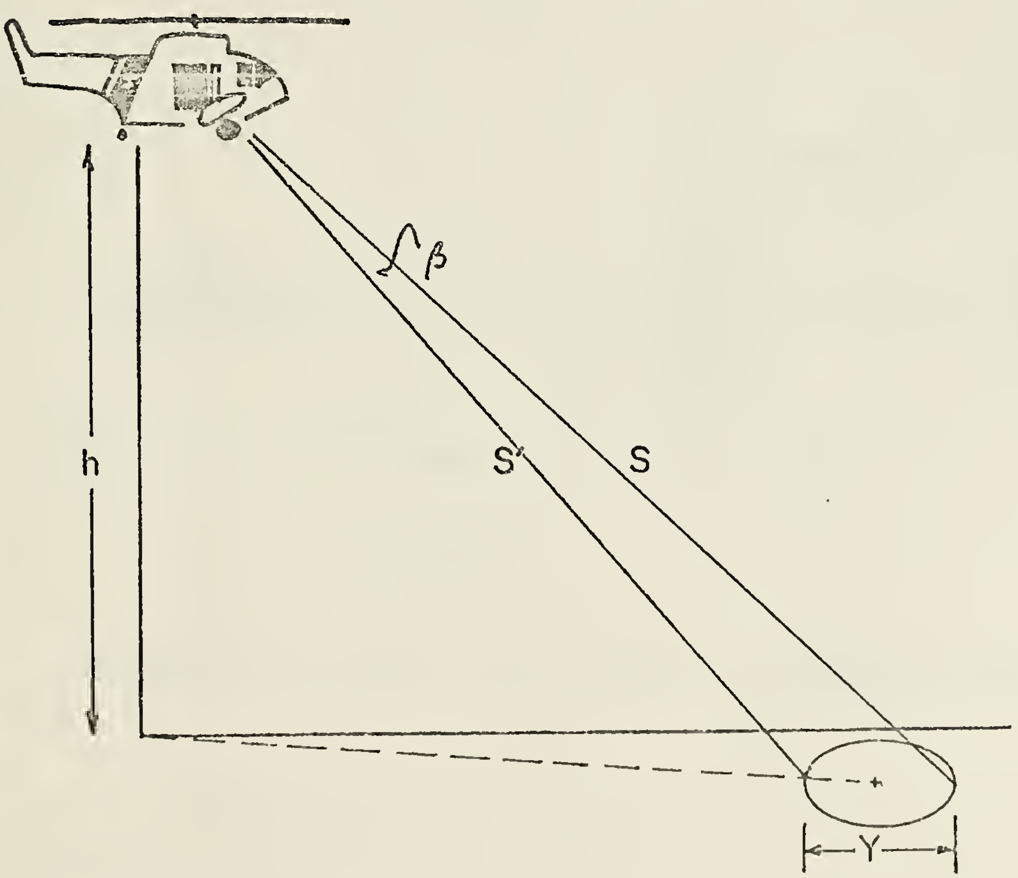

Figure 10. Foveal Vision Area of an Airborne Observer

The foveal vision areas for the search situation previously discussed (500 foot search altitude, $\frac{1}{4}$ mile Track Spacing and Sweep Width) can be found.

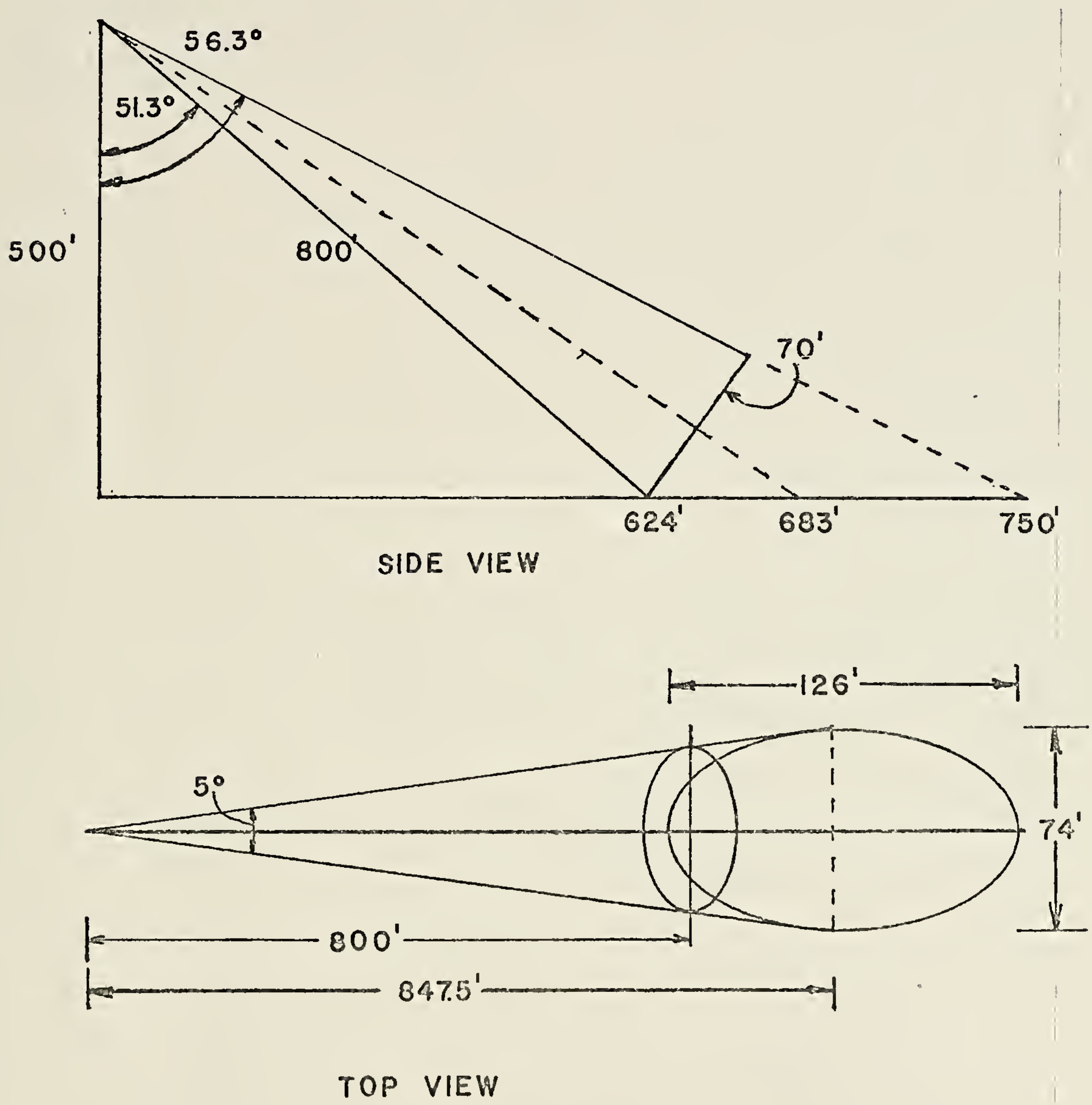

Figure 11. Foveal Vision Area for a Typical Search

The area for the ellipse shown in Figure 11 would be approximately 29,292 square feet. This is the ellipse for the fixation at the edge of the sweep width. Directly under the aircraft the foveal vision area would be circular and equal to 1,497 square feet.

V. EYE MOVEMENT DURING VISUAL SEARCH

Reference 7 describes an experiment in which a subject searched a circular field of 30 degrees of eyeball rotation for five seconds. The target was a one eighth inch diameter spot of white light projected from behind on a white screen at intensities of threshold brightness and slightly above threshold brightness. In a series of 30 exposures (of five seconds each) the target appeared 12 times, and all the following data is from those instances when no target appeared, since the experiment was concerned with search behavior only.

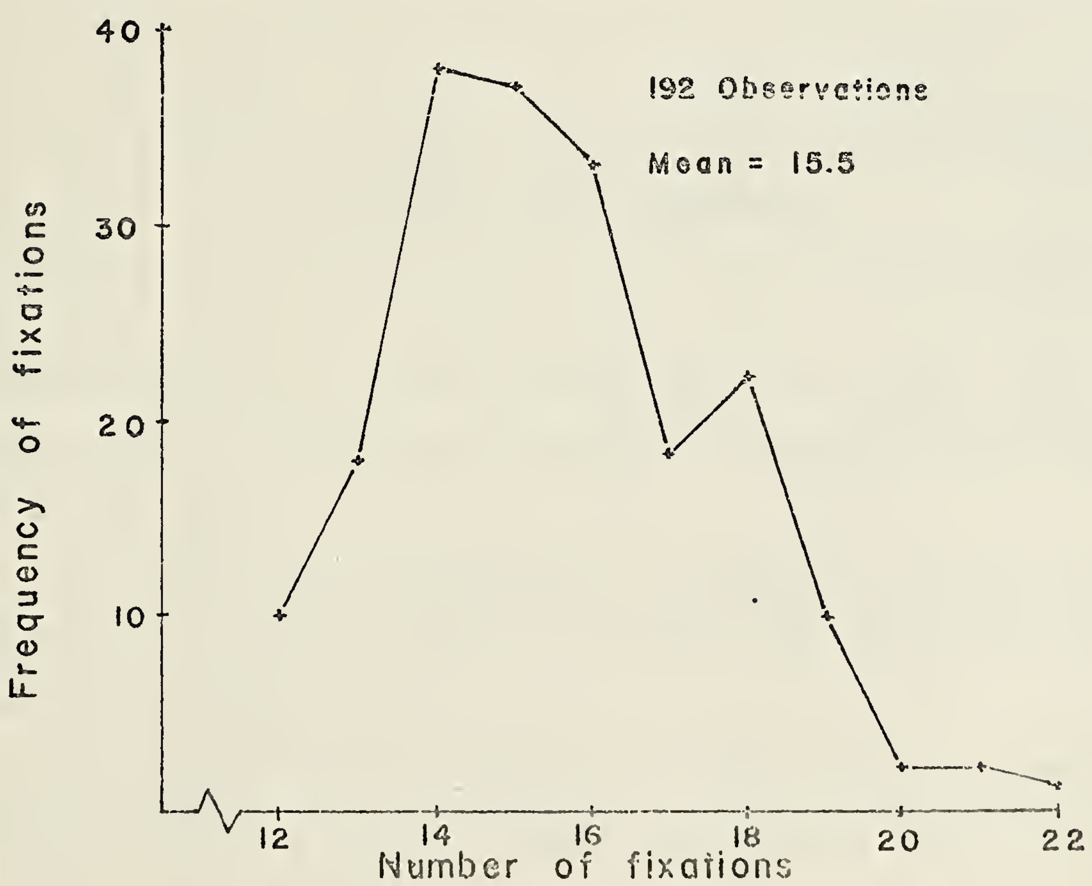

Figure 12.
The Number vs. Frequency of Fixations in Free Search

Figure 12 indicates that three fixations per second is a good estimate of the mean rate of fixations in free search. The duration of fixations (the amount of time spent looking at an object) is shown in Figure 13.

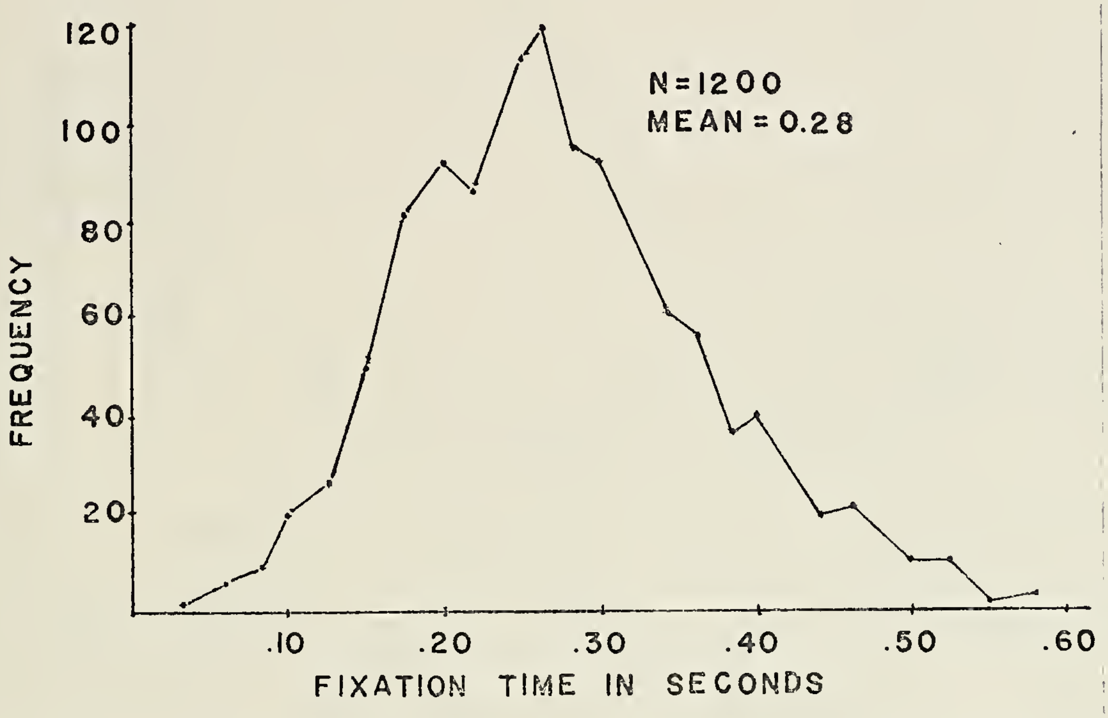

Figure 13. Fixation Time versus Frequency of Fixations

The mean duration of each fixation was 0.28 seconds; the median for the above distribution is 0.27 seconds; the mode is 0.26 seconds.

This means that it takes about ¼ second to visually investigate a circular field of 30 degrees and determine if a target is present.

The experiment also measured the amount of eye movement between fixations and the results are shown in Figure 14.

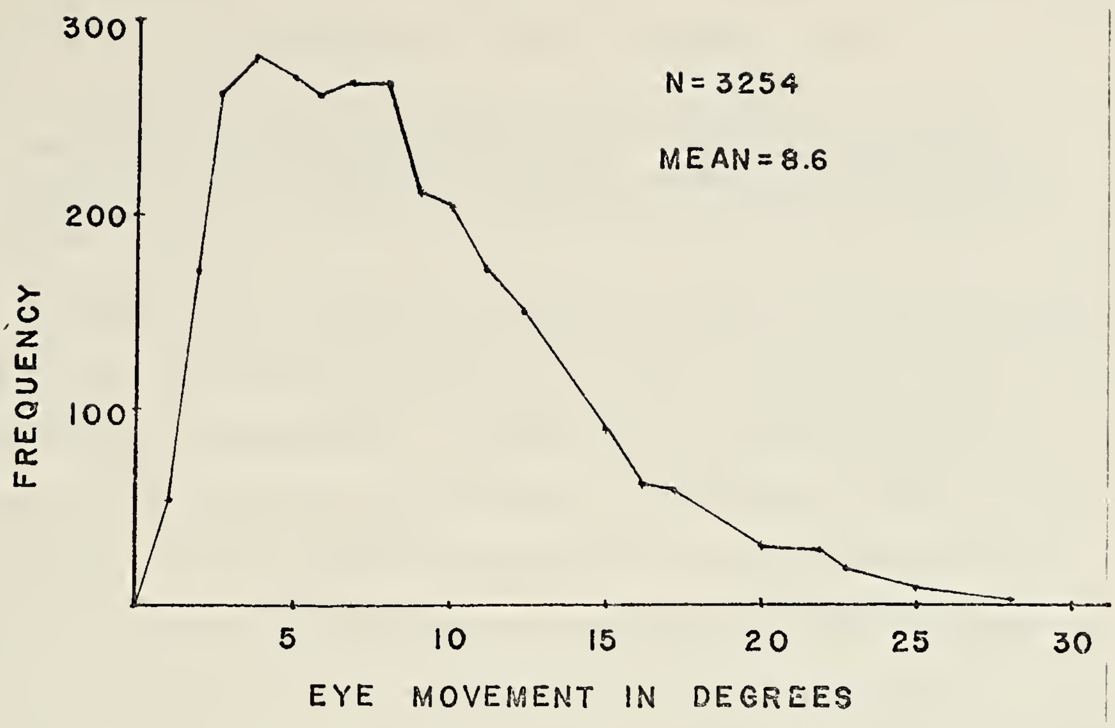

Figure 14. Eye Movement versus Frequency

These results indicate that most observers move the visual axis about eight degrees between fixations.

In summary, based on this experiment, a lookout's visual performance might be modelled thusly:

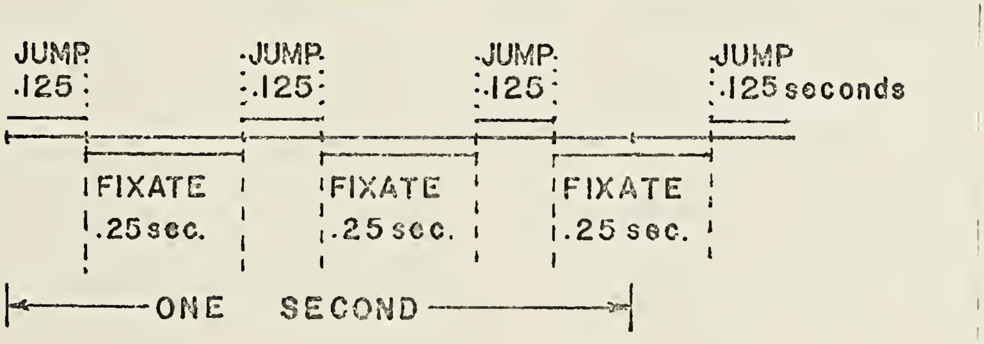

Figure 15. Typical Movement Pattern in Free Search

In contrast to the findings of the preceding study, the National Search and Rescue Manual, CG-308, states:

> "A routine scanning pattern should be used when searching. The eyes should move and pause for each three or four degrees of lateral and/or vertical distance at a rate that will cover about ten degrees per second."

Consider the following situation: an observer is searching at an altitude of 500 feet and uses a quarter-mile track space and sweep width. The angular distance from directly below the aircraft to the limit of the sweep width is about 52 degrees. Using the recommended rate of ten degrees per second, three or four degrees of movement uses up either 0.25 or 0.33 seconds for each jump between fixations. Assuming a fixation duration of 0.25 seconds, then an observer fixates two times every second. In two seconds, an aircraft travelling at 85 knots moves about 2800 feet. With a quarter-mile sweep width, the lookout is looking out to a distance of 750 feet on either side of the aircraft. The search area is 750 times 2800 or 2,100,000 square feet. Therefore, in order to completely cover the area during four fixations, each fixation has to cover 525,000 square feet, i.e., take in an area whose diameter is 818 feet. This seems to be too large an area for a fixation, and in fact the <u>foveal</u> vision area for this fixation would only be about 100 feet in diameter. With wider track spacing and/or sweep widths, a scanning pattern this slow would result in even larger fixation areas and result in poorer area coverage.

The natural jump rate determined in the previously discussed experiments seems to be about eight degrees in 0.125 seconds, or <u>64 degrees per second</u>.

If a lookout wants to maximize the probability of detection, he should cram as many fixations as possible into every second. This can be accomplished by fixating for shorter periods of time (remembering that the fixation time must be long enough for the lookout to make the decision: target is/is not in the area), by fixating for the same length of time but jumping quicker, or a combination of shorter fixations and more rapid jumps.

An increase in search efficiency by decreasing fixation time is a genuine possibility. The normal person's fixation duration is probably quite slow because of at least two factors. One; when individuals read, they vocalize - say, form, or think a word to themselves as they look at it, and this slows down the fixation rate. Two; they are constantly bombarded by commercial advertising which, as H. A. Knoll observes in Ref. 8:

> "The 'Madison Avenue' type spends his working hours devising methods of visual (and other) conspicuousness...he does everything to make the single glance probability equal to unity. His design is to reveal, not to hide - to reduce search to an absolute minimum. Extensive exposure to such simple visual displays may (and this goes beyond what one would call an educated guess) result in eye movement patterns poorly adapted to difficult search tasks."

Therefore, when searching, a conscious effort must be made to overcome this slow eye movement pattern syndrome. Perhaps this can be done by proper motivation. There is

also the possibility that a speed reading course could train an individual to decrease his fixation duration and thus increase his fixation rate.

A. PATTERNED SEARCH STRATEGIES

CG-308 recommends:

> "In the waist, eye movement should be away from the aircraft to the effective visibility and then back towards the aircraft to a point as near the aircraft as can be comfortably seen."

In Ref. 9, a U.S. Army report, four different search patterns were investigated. They were:

1) Forward-fixed method: the lookout looked forward at an angle of 45 degrees to the line of flight and downward to the surface holding his head fixed.

2) Forward-movement method: the lookout looked forward at a 45 degree angle to the line of flight initially, then swept his gaze back toward the rear of the aircraft. The head was moved continuously to provide successive sweeps from fore to aft of the line of sight.

3) Side-fixed method: the observer looked 90 degrees to the line of flight and downward; line of sight was maintained constantly with no eye movement.

4) Side-movement method: the observer swept his gaze inward toward the aircraft and outward toward the horizon. Head movement, rather than eye movement, was stressed in both this and the preceding method.

The search area and aircraft flight path was as shown in Figure 16. Search altitude was 200 feet.

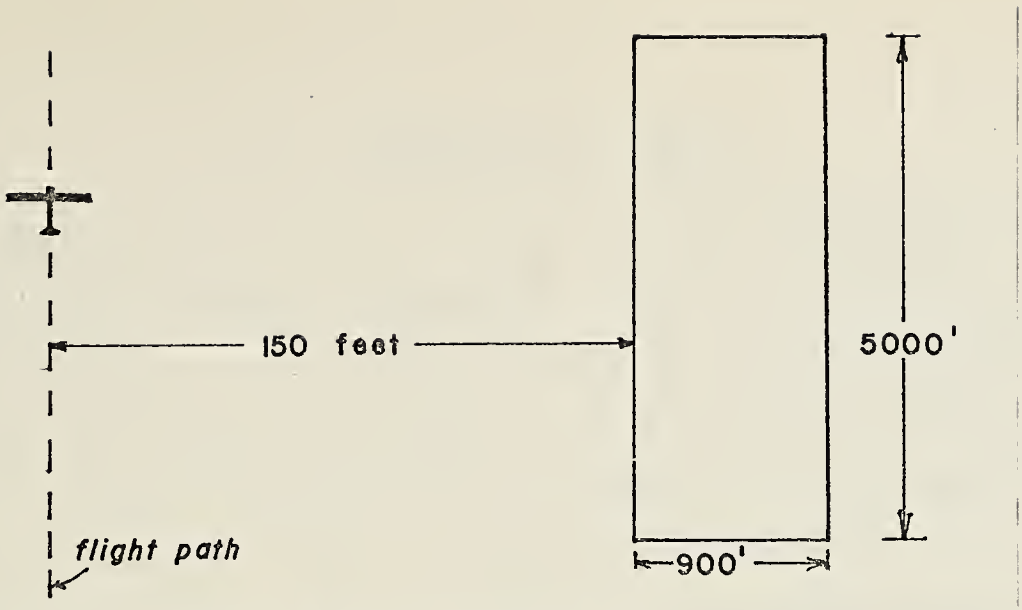

Figure 16. Flight Path of Aircraft in Low-altitude Search

Targets included M-48 tanks, various trucks, trailers, a Browning Automatic Rifle and assorted rocket launchers. Detection performance was scored on a four point scale. A unique description, "M-48 tank" received four points, while "a weapon" received one point with descriptions of intermediate accuracy scored accordingly.

Reference 9 indicated that of the systematic search strategies, the side move method was the most effective and supports the method recommended by CG-308.[2]

---

[2] Reference 1, p. 44 proves mathematically that when most of the relative motion between observer and target is due to the observer, all scanning should be done abeam.

VI. PROBABILITY OF SEEING

Objects become visible when they differ perceptively in brightness from their background. If I is the brightness of the background, and ΔI is the brightness difference between target and background required to make a target visible, then the Weber fraction $\Delta I/I$ is a measure of the perceptible contrast between target and background. The value of $\Delta I/I$ may be positive or negative depending on whether the target is brighter or darker than its background.

Reference 11 used two background brightnesses: 2950 and 17.5 foot-lamberts. The first is approximately equivalent to the brightness of sunlit sand, water and sky; the second is approximately equivalent to the ambient brightness after sunset.

The experimental procedure in the study was to flash targets of various sizes and brightnesses on a 30 degree circular area illuminated at either 2950 or 17.5 foot-lamberts. The observer knew when the target would appear and its approximate position. The operator selected a value of $\Delta I/I$ for each trial and the observer, using <u>direct foveal vision</u>, stated where the target appeared in the field. From a plot of the relation between frequency of correct answers versus log $\Delta I/I$, the operator found the threshold value $(\Delta I/I)$ corresponding to five correct answers out of eight judgments. The exposure time was three seconds and was

considered ample time for one fixation to occur. In fact, in Ref. 12, the threshold contrast $(\Delta I/I)_t$ was measured as a function of the time of exposure to light. For any given background brightness, the product of $(\Delta I/I)_t$ and the time of exposure was constant below a fairly critical exposure time τ. Beyond this critical time, $(\Delta I/I)_t$ was constant.

If the eye remains fixated on a spot for a time greater than τ, no increase in chance of seeing can be expected through further increase in fixation time. For the two luminances 2950 and 17.5 foot-lamberts, τ is estimated to be about 0.024 and 0.046 seconds respectively, therefore three seconds is more than enough time for the chance of seeing to have reached its maximum value.

The fact that more than one fixation could have occurred during this period has been considered. However, some of the observers stated they had reamined fixated on a reference spot during the entire exposure and there was no significant difference in the shape of their frequency of seeing curve when compared to the curves for the observers who fixated more than once.

According to the quantum theory of light, (see Appendix A), light is emitted and absorbed as discrete quanta of given energy content. These quanta are absorbed by the receptor elements in the retina and this absorption constitutes the initial event in the vision process. In this study, the retinal receptors were considered to be those in the foveal area which to a large extent are each connected to a

single ganglion fiber of the optic nerve. Since each quantum absorption by a foveal cone must be considered an independent and random event, the whole foveal vision process may be considered from the point of view of probability theory.

Consider a situation in which a "trial" is made, for example the toss of a fair coin ("fair" means the coin has just as good a chance of coming up heads as it does coming up tails), the rolling of a die, or the incidence of a quantum of light on the fovea. Let the probability of success in the trial be p and the probability of failure be q. Since the trail must either succeed or fail, $p + q = 1$ or 100 percent.

To find the probability of a given number of successes out of a specified number of trials, the <u>binomial theorem</u> says the probability of exactly n successes out of m trials is the n^{th} term in the expansion of $(p+q)^m$. To illustrate:

$$(p+q)^m = q^m + mq^{m-1}p + m(m-1)q^{m-2}\frac{p^2}{2!} + \dots \qquad (5)$$

The zeroth term, q^m is the probability of complete failure in m trials. The first term, $mq^{m-1}p$ is the probability of exactly one success, and the second term, $m(m-1)q^{m-2}\frac{p^2}{2!}$ is the probability of exactly two successes.

Poisson showed that if p is small compared to one (1.0), each term in the binomial expansion can be approximated quite accurately by a simpler expansion in terms of the expected number of successes ε defined as the product of p, the probability of success per trial and m, the total number

of trials. In other words,

$$\varepsilon = mp \tag{6}$$

Now the probability of exactly n successes, p_n, in m trials is given by Poisson as

$$p_n = \varepsilon^n e^{-\varepsilon}/n! \tag{7}$$

where e is the base of the natural logarithms.

The probability P_n of at least n successes out of m trials is given by

$$P_n = \sum_n^m (\varepsilon^n e^{-\varepsilon}/n!). \tag{8}$$

For finite values of ε, if p is small, m must be large so that

$$P_n = \sum_n^\infty (\varepsilon^n e^{-\varepsilon}/n!). \tag{9}$$

Both p_n and P_n have been computed for various values of ε and n and can be found in published tables.

In this study, Eq. (9) represented the probability that n or more quanta would be absorbed by the retina when it was given an exposure to light of such intensity that <u>on the average</u>, ε quanta were absorbed by the retina from it.

The incidence of a light quantum on the retina and its subsequent absorption by a cone is not a predictable event but rather one that is subject to statistical fluctuations.

When a light quantum is incident on the fovea, it is absorbed by a cone or it is not absorbed. The probability p that a light quantum is absorbed by a cone depends upon

the concentration of the photosensitive substance, probably iodopsin, in the cone. This concentration in turn depends upon the background brightness through its influence on the stationary state concentration of the photosensitive substance. For any given background brightness, the concentration of sensitive material is constant and therefore the probability of absorption p is constant. In addition to the quanta from the background, those supplied by the ΔI field in a definite time (probably less than 0.1 second), must also be considered. Remember ΔI is the brightness added by the target.

The basic assumption has been that in order for a target to become visible, a certain number of quanta n must be absorbed in some manner and in some location by the cones. Assume that the area within which n or more quanta must be absorbed is restricted to one or more sections of a narrow strip of retinal cones just inside the image boundary. This means that the presence of a target will be detected if one or more small segments of the perimeter each absorbs n or more light quanta. The probability that at least n light quanta will be absorbed in a given section of the boundary is P_n. The probability that less than n quanta will be absorbed in the given section is $1-P_n$. If there are k sections around the image perimeter, then the probability that less than n quanta will be absorbed in each of the k sections is $(1-P_n)^k$. Therefore, the probability that at least n quanta will be absorbed in at least one of the k sections is

$$P = 1-(1-P_n)^k \qquad (10)$$

which is also the probability of seeing the target.

Assuming Eq. (10) is a satisfactory one for cone vision in the fovea then it must be possible to find a value of n which is the same for all sections of the image perimeter. It must also be possible to find a unit section such that if the number k of sections around a given image perimeter is substituted in Eq. (10), the resulting frequency-of-seeing curve will have the same shape as the experimental one for the given image. This must be true for all sizes and symmetries of the targets.

To find the minimum number of quanta n required for detection of the target and the size of the unit section of the perimeter within which the number of quanta must be absorbed, the measurements in Figure 17 are helpful. This graph shows the relationship between the probability of seeing and the contrast for an image whose average perimeter is 6.3 minutes (and whose average number of cones along this perimeter is ten) with a target background brightness of 2950 foot-lamberts. Since this graph shows the measurements for the smallest target, the number k of unit sections is sure to be the minimum for the targets investigated in this study.

Selecting an arbitrary trial value for n and computing P_n as a function of the expected average number of quanta ε using Eq. (10) yields various values for P_n. Then for each

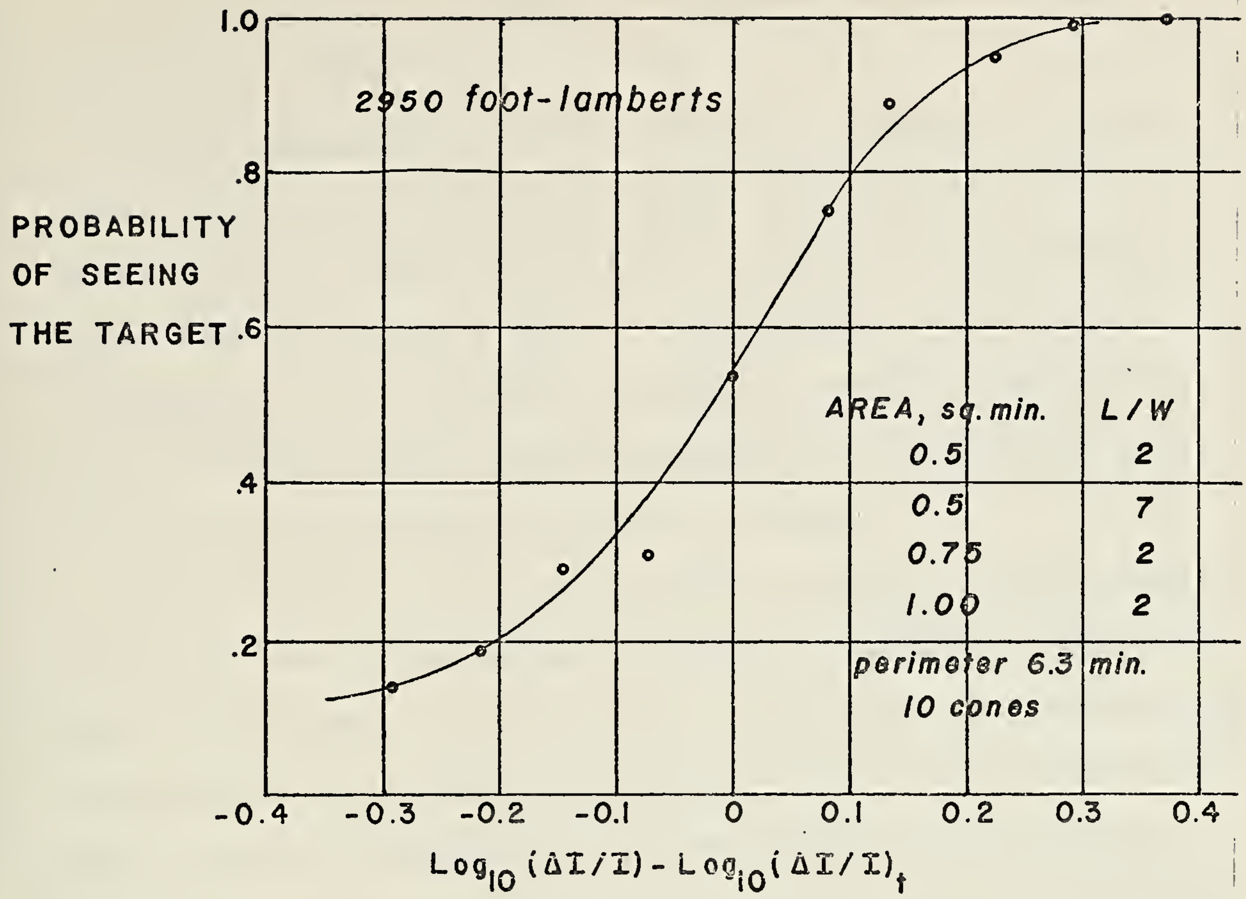

Figure 17. Probability of Seeing Graph

P_n value obtained in this way, a P is computed using Eq. (10) and a series of values for k. If these computed values are plotted as a family of curves, one curve for each value of k, with the probability of seeing P as ordinate, and $\log_{10}\varepsilon$ as abscissa, then for the same scales as in the preceding graph, a comparison of computed and actual frequency of seeing curves can be made until the value of k is found whose curve best fits the points. If the entire procedure is repeated for other values of n and the best value of k is found in each case, a pair of values of n and k can be found whose curve gives the best fit for the points in Figure 17.

For the points in Figure 17 the best pair of values is $n = 4$ and $k = 10$.

The significance of these results is that at least one unit segment of the image perimeter must absorb n (4) or more quanta to render the target visible. In other words, this seems to be the number of light quanta which must be absorbed by a unit segment in order to release impulses in the associated nerve fiber and result in vision regardless of the state of adaptation of the retina.

The value of k also has a simple meaning. The frequency of seeing data on the graph are for the smallest targets at high brightness. The geometrical images of these targets on the retina are all smaller than the diffraction pattern of a point source as produced by the 2-millimeter artificial pupil, and the targets may therefore be thought of as point targets. Computations have shown [Ref. 13] that the central disk of this diffraction pattern is two minutes visual angle. Its perimeter is therefore 6.3 minutes. Since k, the number of visually significant sections in this perimeter, is ten, each section is 0.63 minutes long. This distance is the same as the diameter of a foveal cone. Osterberg [Ref. 14] gives 0.55 minutes as the distance between cone centers in the densest region of the central fovea; for the slightest increase in distance from the central fovea these distances increase rapidly. However, since this study covers observations made with the most central region of the fovea, 0.55 minutes is an acceptable value. It is therefore probable

that the length of a visually independent section of the image perimeter is actually the diameter of a single cone. The difference between 0.55 minutes, the measured cone diameter, and 0.63 minutes, the computed diameter of a visually independent segment merely says that the critical cones do not lie with their centers on the periphery of the diffraction disk, but that they lie just within this perimeter.

The length of the unit section of the periphery may thus be considered as the diameter of a foveal cone. From the concept of physiologically useful flux it is known that for a brightness of 2950 f-1, the width of the useful ribbon inside the perimeter of the target does not exceed one minute. Since this width is not wide enough for two cones, it seems reasonable to suppose that a visually independent section consists of a single foveal cone, and that this is the primary visual unit in the contrast recognition of targets. If this is accepted, then k which appears in Eq. (10) can be considered as the perimeter of the retinal image of the target as measured in cone diameters.

Equation (10) holds for the other frequency-of-seeing curves also. Experimental results of this study are shown on Figure 17 and in Tables I and II.

If the value n = 4 is substituted into Eq. (10), and k is given specific values corresponding to the number of cones the perimeter of the target, then computed frequency-of-seeing curves are identical to observed frequency-of-seeing curves.

TABLE I

Relationship between probability of seeing and contrast for images of various perimeters with a target background brightness of 2950 foot-lamberts.

log ($\Delta I/I$) - log $(\Delta I/I)_t$	Image perimeter in minutes 6.3	12.5	19	31	115	168
-0.291	0.143	0.107	0.19	0.096		0.500
-0.218	0.184	0.134	0.035	0.026	0.184	0.000
-0.146	0.282	0.181	0.199	0.211	0.233	0.232
-0.073	0.300	0.327	0.358	0.362	0.374	0.312
0.000	0.540	0.550	0.553	0.584	0.578	0.552
0.073	0.750	0.764	0.733	0.741	0.781	0.845
0.146	0.883	0.875	0.865	0.919	0.890	0.895
0.218	0.956	0.960	0.977	0.975	0.985	0.985
0.291	0.987	1.000	1.000	0.971	1.000	0.980
0.364	1.000	1.000	1.000	1.000		

(Column values are the probability-of-seeing)

TABLE II

Relationship between probability of seeing and contrast for images of various perimeters with a target background brightness of 17.5 foot-lamberts.

log ($\Delta I/I$) - log $(\Delta I/I)_t$	Image perimeter in minutes 9.4	13.5	20.4	32	98	169
-0.364	0.000	0.000				0.000
-0.291	0.000	0.071	0.000			0.083
-0.218	0.198	0.097	0.017	0.047	0.120	0.130
-0.146	0.234	0.241	0.224	0.143	0.180	0.222
-0.073	0.431	0.468	0.373	0.420	0.313	0.355
0.000	0.572	0.589	0.518	0.517	0.563	0.555
0.073	0.714	0.689	0.745	0.781	0.810	0.714
0.146	0.875	0.832	0.917	0.940	0.880	0.913
0.218	0.937	0.960	1.000	0.968	1.000	0.953
0.291	1.000	0.965	0.960	1.000	0.955	1.000
0.364	1.000	1.000				

To determine the number of cones k in the perimeter of the target image, Ref. 14 provides measurements which can be used to construct Figure 18.

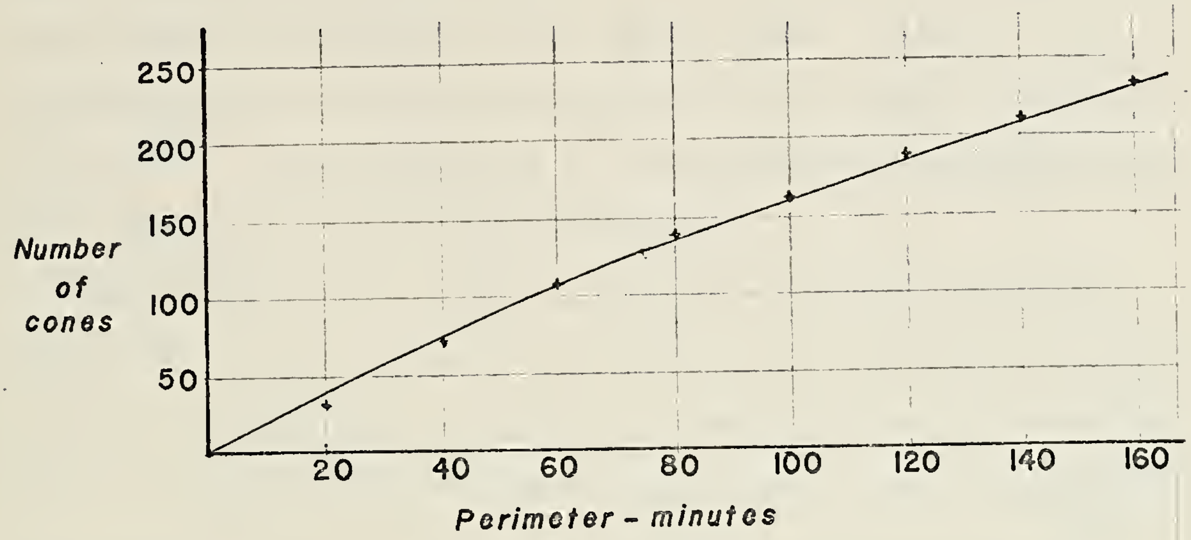

Figure 18. Number of Cones in the Image Perimeter as a Function of the Length of the Perimeter

In summary then, the probability of exceeding the threshold and seeing the target is computed using the formula:

$$P = 1-(1-P_n)^k$$

where

$$P_n = \sum_{n}^{\infty} (\varepsilon^n e^{-\varepsilon}/n!)$$

and represents the probability that n or more quanta would be absorbed by the retina when it was given an exposure to light of such intensity that, on the average, ε quanta were absorbed by the retina from it.

Results of this study, [Ref. 13], indicated that n equalled four quanta and k equalled the number of cones in the target's perimeter image.

Since this experiment was conducted so that the observers were using direct foveal vision only, these results indicate that within the foveal vision area, at least four quanta of light must be absorbed by one foveal cone. Further, the probability of detection increased as the number of quanta increased. The probability of detection also increased with an increase in the target's perimeter.

This thesis will apply the results of this experiment [Ref. 13] to the operational situation faced during a typical search. It should be remembered however, that the results obtained in Ref. 13 were from experimental situations which are much different from those encountered during a normal search from a Coast Guard aircraft. In other words, in an operational search, the number of quanta required for detection might be six instead of four, but the basic hypothesis would still be valid.

Consider a searcher using foveal vision in an airborne search for a target whose contrast is constant. Then, assuming that the target comes within the searcher's view, the probability of detection becomes a function of the size of the target. More precisely, the probability of detection is a function of the solid angle subtended by the target at the searcher's eye. Note the solid angle is equal to the area of the target's image on the fovea divided by the square of the distance from the optical center of the eye to the fovea, (see Figure 19).

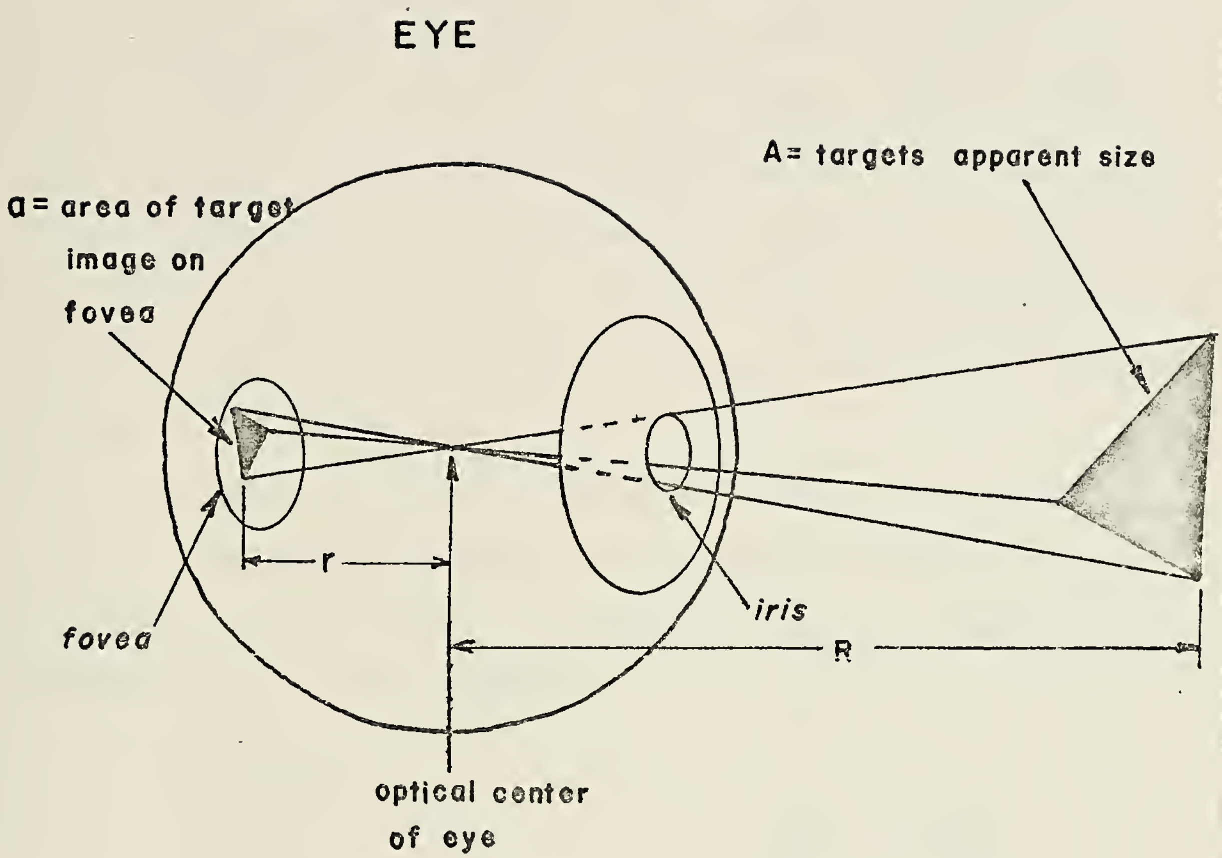

Figure 19. The Solid Angle of the Target

VII. THE INVERSE CUBE LAW OF DETECTION

In the preceding section on probability of seeing, experiments indicated a relationship between the number of quanta absorbed by the retina in some unit length and the probability of seeing the target (probability of detection). Since the number of quanta absorbed is directly proportional to the size of the target, the probability of detection is a function of the target's size, or put another way, the solid angle of the target.

In a typical encounter between a stationary target and a moving searcher, the target will enter the lookout's "zone of detection" and follow some line of relative motion. The encounter might look like this:

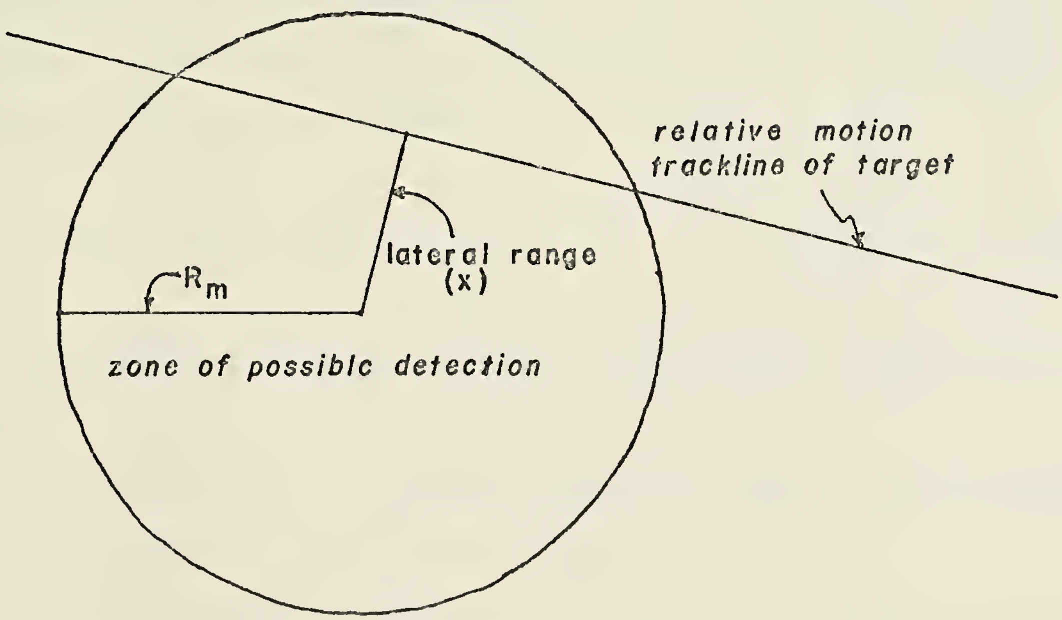

Figure 20. Zone of Detection

The probability of detecting a target which passes at some lateral range (x) can be graphically represented by a lateral range curve. This curve shows the probability of detection, P(x), for a given set of environmental conditions, for the period that the target is within the zone of detection. A typical lateral range curve is shown in Figure 21.

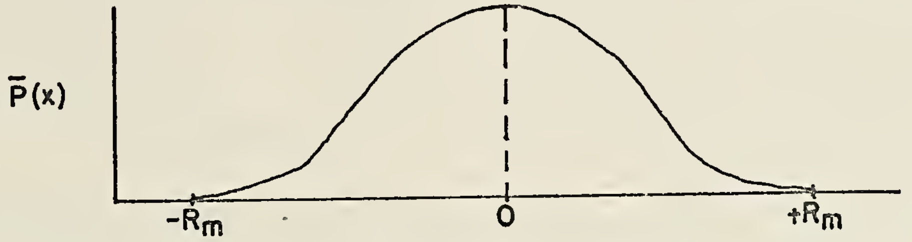

Figure 21. Lateral Range Curve

For a parallel sweep search pattern the probability of detection can be found if the track spacing, S, is known. The track spacing is the distance between adjacent search tracks. The sweep width, or area swept out by the search device, is W and is given by

$$W = \int_{-R_m}^{R_m} p(x)dx \tag{11}$$

Under the assumptions of the inverse cube law of detection:

1) The lookout is at some height h above the surface on which the target is located.
2) The target's range r is much greater than the search altitude, h.
3) The probability of detection per unit time is proportional to the solid angle of the target.

For a particular value of track spacing, the probability of detection as a function of track spacing is [Ref. 15, p. 51]:

$$P(S) = 2 \int_0^z f(t)dt \qquad (12)$$

where f(t) is the standardized normal distribution with zero mean and variance one and

$$z = W/S$$

$$= 1.25\ W/S.$$

For example, if W = 48.6 and S = 60, then

$$z = 1.25\ W/S$$

$$= 1.015$$

and the probability of detection when S = 60 and W = 48.6 would be:

$$P(60) = 2 \int_0^{1.015} f(t)dt$$

$$= 0.6898$$

Equation (12) is used to generate the probability of detection graph (Figure 7-4) in the National Search and Rescue Manual.

VIII. RANDOM SEARCH

Suppose the position of the target in the search area A, is considered to be randomly distributed, i.e., the target is as likely to be in one part of A as any other. Also assume that the lookout searches the area using a random search pattern. What then is the probability that detection will occur by the time the lookout has travelled L miles through the search area?

Again, let P(x) be the lateral range curve for the lookout and this target in this particular environment. If there is some chance that the target will be detected, i.e., its lateral range is some value between $-R_m$ and $+R_m$, and if the target is just as likely to follow a relative trackline through the zone of detection at one lateral range as any other lateral range, then if a random variable, X, is defined as the lateral range to the target, then X has a uniform probability distribution over the range of values from $-R_m$ to $+R_m$. The probability density function can be defined for X:

$$f(x) = \begin{cases} \dfrac{1}{2R_m} & -R_m < x < +R_m \\ 0 & \text{elsewhere} \end{cases}$$

Since the function P(x) gives the probability of detecting a target given a specific lateral range x, the probability of detecting a target whose lateral range is random is

$\overline{P}(x)$, which is the unconditioned p(x), may be thought of as the expected or average value of p(x).

$$\overline{P}(x) = \int_{\text{all } x} P(x)f(x)dx \tag{13}$$

In this case, since x is uniformly distributed between $-R_m$ and $+R_m$,

$$\overline{P}(x) = \frac{1}{2R_m} \int_{-R_m}^{R_m} P(x)dx = \frac{W}{2R_m} \tag{14}$$

If the lookout's path is divided into N segments of equal length L/N, each approximating a straight line, then Figure 22 illustrates the relationship between the area searched,

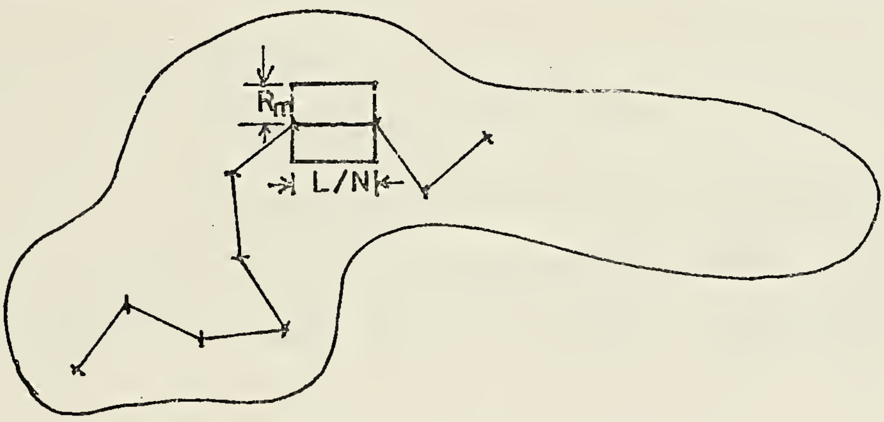

Figure 22. Random Search Pattern

For detection to take place in the first track segment, two events must occur. Let B be the event that the target is in the area of length L/N and width $2R_m$, so that there is some chance of detection occurring, and let C be the event that the target is detected; then:

$$P(B) = \frac{2R_m L/N}{A} \tag{15}$$

and

$$\overline{P}(x) = \int_{-R_m}^{R_m} P(x)f(x)dx \tag{16}$$

Therefore, the probability of detection in the first or any other single segment is

$$P(\text{detection}) = P(C \cap B)$$

$$= P(C/B)P(B)$$

$$= \frac{2R_m L/N}{A} \cdot \frac{1}{2R_m} \int_{-R_m}^{R_m} P(x)dx \tag{17}$$

which can be rewritten as

$$P(\text{detection in any one segment}) = WL/NA \tag{18}$$

The probability that detection fails to occur during this search of N segments of equal length would then be $1-(WL/NA)^N$, assuming independence; and the probability of detection is then

$$P(\text{detection}) = 1-(1-WL/NA)^N \tag{19}$$

note

$$(1-WL/NA)^N = e^{N \ln(1-WL/NA)}$$

which is approximately equal to $e^{-WL/A}$, since when WL/NA is small,

$$\ln(1-WL/NA) = -WL/NA.$$

With this approximation, the probability of detection in the random search model now becomes

$$P(\text{detection}) = 1-e^{-WL/A} \tag{20}$$

provided the fraction of the area effectively covered on each segment, WL/NA, is small.

In summary, the random search model is based on the following assumptions:

1) the targets position is fixed and randomly distributed in A,
2) the search is conducted in a random manner such that its individual segments can be considered to be independent of each other,
3) $2R_m$ is small compared to L/N so that missed areas and overlaps at the end of each segment can be neglected.

This model represents a search in which the least information is known about a target and no systematic search plan is used. Hence, in the case where more is known about a target and a systematic means of searching is used, an equal amount of search effort should yield a higher probability of detection.

The quantity WL/A is called the coverage factor and is a measure of the percentage of the search area visually investigated.

Figure 23 shows the way in which the cumulative probability of detection in a random search increases with the coverage factor. It can be seen that when the coverage

factor is small, the probability of detection is approximately equal to the coverage factor itself. When the coverage factor is larger, the probability approaches a value of one [Ref. 15, p. 111]

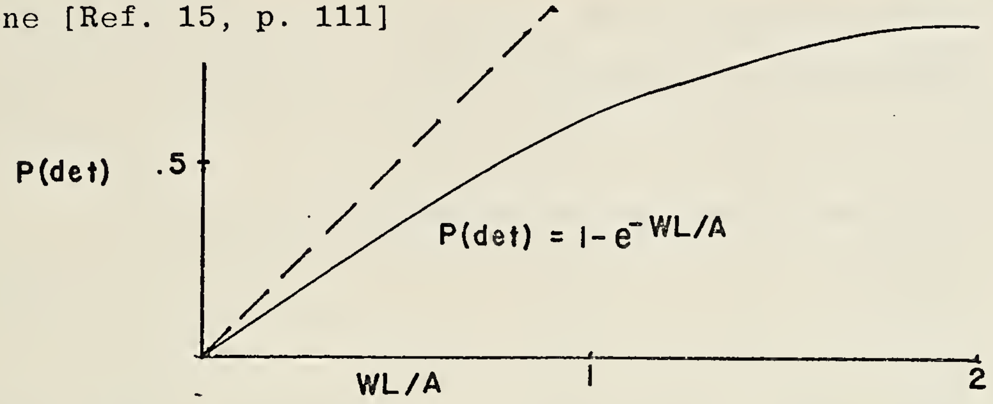

Figure 23. Probability of Detection vs. Coverage Factor for a Random Search

A comparison of the probability of detection curves plotted as functions of coverage factor for the random search model and a parallel track search with the inverse cube law of detection is shown by Figure 24. In this case, the random search is assumed to be conducted in the same area as that of the parallel sweep search.

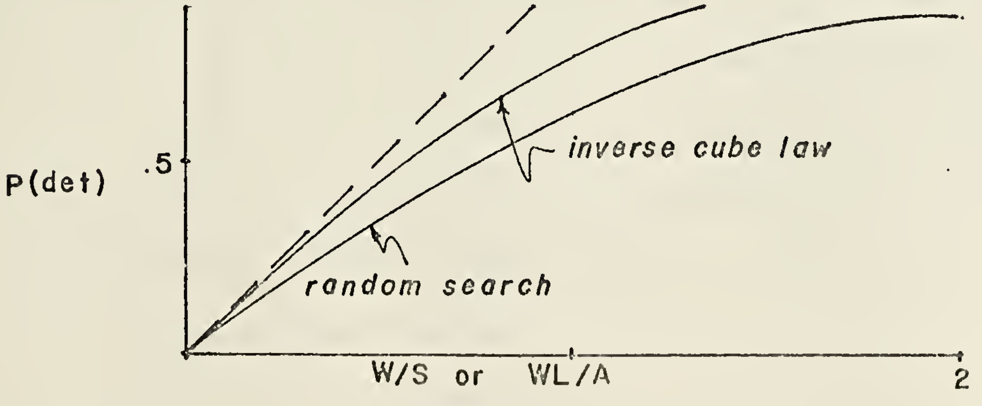

Figure 24. Probability of Detection vs. Coverage Factor for Random Search and for Inverse Cube Law Search

The dotted lines in Figures 23 and 24 represent the probability of detection in a systematic search, that is one with no overlapping of swept areas, using a "cookie cutter" detection device. A cookie cutter detection system has a lateral range curve of the type shown in Figure 25.

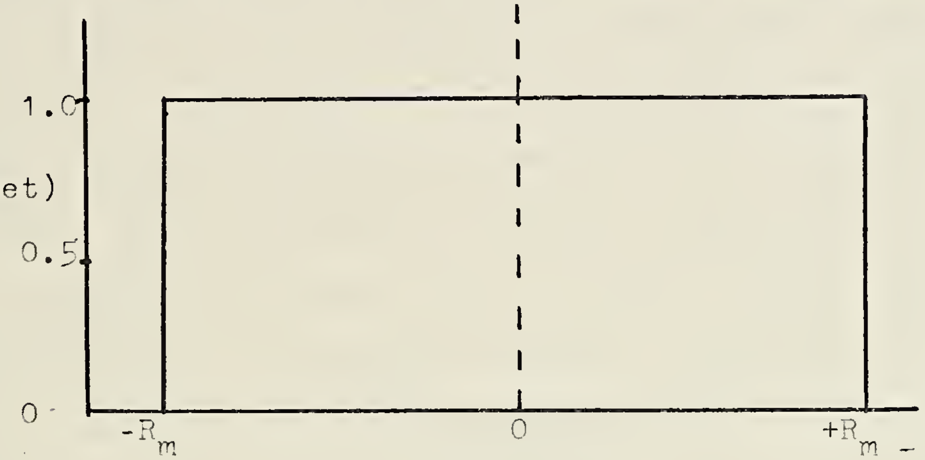

Figure 25.

The Lateral Range Curve for a "Cookie Cutter" Detection System

Thus any target that comes within the maximum range of the system is detected with a probability of one.

Since there is no overlap of swept areas, the probability of detection would equal A'/A where A' is the area swept out by the detection system and A is the total search area.

For a parallel track search, A' would equal nW where n is the number of tracks and W is the sweep width and A would equal nS where S is the track spacing. Thus:

$$\begin{aligned} P(\text{detection}) &= A'/A \\ &= nW/nS \\ &= W/S. \end{aligned}$$

When there is no overlapping of possible detection zones, and when the value of the coverage factor is small, the coverage factor itself is a good estimate of the probability of detection. The random search models estimate the probability of detection when little is known about the target's location and no systematic search plan is used. It might be a better estimate of the probability of detection when the search aircraft is unable to fly a precise search pattern, either because of limited navigational facilities or because the aircraft has to deviate from the search track occasionally to investigate possible targets and, as a result does not fly a uniform search pattern. The difference between the probability of detection for random search and for inverse cube law parallel sweep search is small, and the inverse cube law is the model which is used for operational situations. The assumptions underlying the Probability of Detection curve in the National Search and Rescue Manual should be remembered however, and if a search is being conducted where the search patterns can be considered to be <u>random</u> and a conservative estimate the probability of detection resulting from that search is desirable, then the probabilities from the random search model curve should be used in lieu of the inverse cube law curve.

APPENDIX A

LIGHT AND THE QUANTUM THEORY

Visual sensation occurs when the retina is stimulated by a type of radiant energy called light. Radiant energy is energy that travels through space without any apparent vehicle although it has a finite velocity. It is periodic with respect to both space and time.

The propagation of radiant energy occurs by electromagnetic waves and light obeys the laws of classical wave theory. However, in regard to the interaction of light with matter, it is preferable to think of light as a stream of small packets of energy called quanta (or photons). Exchanges between matter and radiation are thought to take place in exact multiples of a small fundamental unit, the quantum. The quantum theory states that the smallest amount of radiant energy that a molecule can emit is one quantum. The energy content, E, of a quantum is dependent on the frequency of the radiation and is given by E = h times f, where h is the universal constant of action (Planck's constant, equal to 6.625×10^{-27} erg-sec.). Thus the energy content of a single quantum, or the work it can do, is directly proportional to the frequency of the radiation (and inversely proportional to the wavelength). Because of this relationship, the higher the frequency of radiation, the greater the possible effect.

It is customary to identify radiation by wavelength rather than frequency. Wavelength and frequency are related by the formula $c=f\lambda$. Where c is the velocity of radiant energy through empty space and equals 3×10^{10} cm. (186,000 mi.) per second. The wavelength of the energy is λ and f is its frequency. The wavelength of visible light ranges from about 380 to 760 mμ (millimicrons; 1 mμ=0.001μ or 10^{-7} cm.) [Ref. 10].

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